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SLICKS AND TEMPERATURE STRUCTURE IN THE SEA

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THE PROBLEM

Investigate oceanographic factors which may be pertinent to the behavior of underwater sound. In particular investigate the vertical fluctuations of temperature and their relation to sea surface slicks.

RESULTS

1. The depth of isotherms in the shallow summer thermocline fluctuates virtually all the time. At Mission Beach, California, of the significant vertical oscillations of a central isotherm in the thermocline, half were greater than 7.2 feet and half had periods greater than 7.6 seconds. Because the internal waves were refracted, they usually proceeded in a general shoreward direction at the measurement site where they had an average speed of 0.31 knot.
2. Every large internal wave of height greater than 14 feet had a sea surface slick associated with it for the thermocline depths observed.
3. In accordance with wave motion theory of simple internal waves, an active convergence circulation occurs over the descending slope of an internal wave. In 85 cases out of 105 at the measurement site, the slick occurred between the crest and the following trough. The relationship was sufficiently reliable to provide an approximate prediction of the subsurface thermal topography from a knowledge of the distribution and movement of the slicks.

RECOMMENDATIONS

Continue the general study of the near-shore and near-surface environmental characteristics which affect acoustic transmission. Give special emphasis to long duration waves and to the geographical distribution of internal waves. Study acoustical transmission through internal waves.

ADMINISTRATIVE INFORMATION

The work reported here was carried on in the Signal Propagation Division under IO 15401, NE 120221-847.13 (NEL L4-1) during the period June 1958 and July 1959 and was approved for publication 2 November 1959.

Many of the sea measurements were made by O. S. Lee, C. D. Curtis, J. C. Roque, and J. S. Black. Much of the data processing was done by A. L. Moore. The bridge circuits and compensating resistor circuit in the thermistor line were designed by A. T. Burke, the thermistor mountings were designed by J. C. Roque, and the beads were cast in plastic by R. L. Arthur. Helpful suggestions were made by G. H. Curl.

The bridge system was built by Hartley Herman of Kahl Scientific Instrument Company, El Cajon, California.

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INTRODUCTION

Slicks are streaks or patches of relatively calm surface water surrounded by rippled water. The absence of wavelets in a slick gives it a glassy appearance in contrast to the adjacent rippled water (fig. 1).

From most angles of view, slick areas appear brighter than the surrounding water during the day because the smoother area reflects the sky light better than the rougher area. In the night, at locations where there is some ambient light, slicks appear darker than the adjacent water because they reflect the black sky better. They also appear darker in bright sunshine when the angle of view is such that the light is directly reflected toward the viewer, because they do not produce a glitter that results from the mutual reinforcement of the reflected rays from the surrounding ripples. Schuleikin¹ (see list of references on page 27) attributed



Figure 1. Examples of sea surface slick.

the difference in appearance between slicks and surrounding water to the reduction in average angle of reflection caused by the capillary wavelets.

Thus, slicks are identified by their difference in optical properties from those of their surroundings. As one gets closer to a slick, however, this difference becomes less obvious.

Slicks have been observed around the world in the open sea, bays, and lakes.¹⁻⁴ According to these investigations, slicks are almost always present when the wind is just strong enough to ripple the water, yet not strong enough to cause whitecaps (Beaufort force 3, i. e., 3.4 meters per second). Frequently, slicks take on the shape of broad, spiderweb-like connecting bands. Occasionally, they occur as isolated patches. In shallow waves over the continental shelf, they often appear as long bands, more or less parallel to the coast. Near shore, a patch or wide band may develop just beyond the breaker zone. Other slicks are found over kelp beds.

The cause of slicks has been studied by several investigators. Ewing^{5,6} concluded that band slicks are associated with long internal waves in a shallow, lowered thermocline. Since the internal waves are of a progressive nature, and since the slick lies over the trough, it must move in the direction of travel of the internal wave.

Dill and LaFond⁷ found a lowering of the thermocline in slicks and, in addition, observed that the turbidity of the water near slicks was different from that of adjacent water. They also made related studies of circulation, surface tension, and other features. The present report covers a continuation of this work, particularly the relation of the temperature structure of the sea to slicks.

MEASUREMENTS

Temperature

Early in the work on temperature structure, it became evident that a need existed for some means of recording temperatures at a number of different points in the sea, simultaneously and continuously, over extended periods of time. For this purpose, an instrument was developed that will record temperatures at as many discrete points (up to sixteen) as may be desired. This instrument has proved very successful.

The recording instrument consists essentially of a string of thermistor beads which are part of a bridge circuit which feeds into a Brown recording potentiometer.⁸ Although sixteen channels and sixteen sensing units can be used, only six beads were used for this study. The beads were arranged so that five of them each actuated three different channels. This reduced the time interval between recordings on the same bead to about 10 seconds. The sixth bead was placed near the surface and recorded about twice a minute. Other details of the instrument are given in the Appendix.

Temperature measurements were made from anchored ships off Mission Beach, California, on twelve days between 12 June and 8 August 1958 (fig. 2A). The procedure was to anchor both fore and aft about 1000-1100 and remain there, recording temperature structure continuously until midafternoon, when the wind usually became strong enough to dissipate the slick. The vertical string of sensing elements was buoyed out slightly seaward, about 100 feet from the anchored ship in 50-foot deep water (fig. 2B). The beads were suspended at 2, 9, 16, 23, 30, and 37 feet from the surface buoy. As a slick approached the buoy supporting the

A

MEASUREMENT
SITE

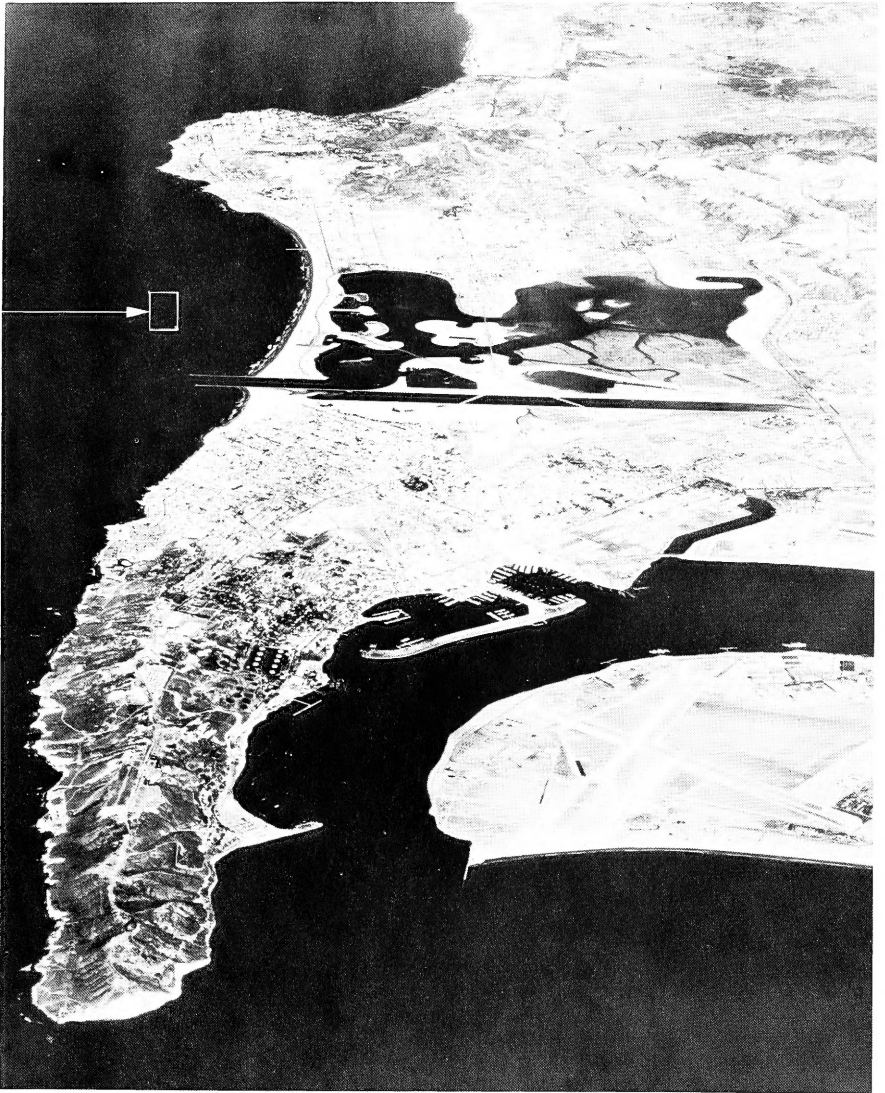


Figure 2A. Measurement site off Mission Beach.

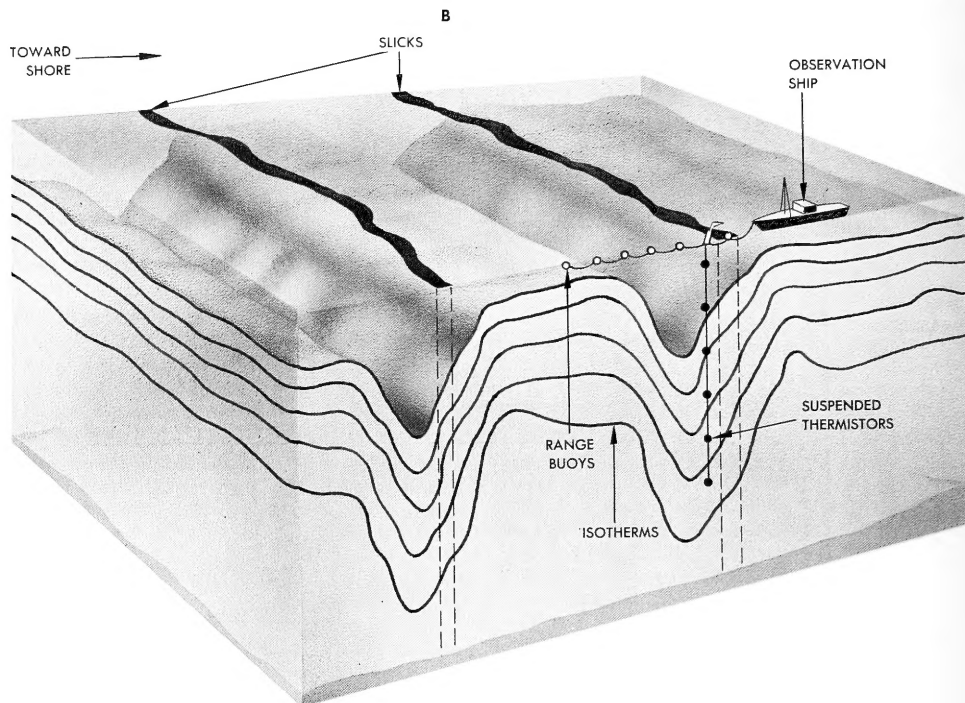


Figure 2B. Measurement arrangement of ship and thermistor beads.

beads, its range from the buoy was noted on the recording tape. This distance was determined visually by reference to a string of surface range markers buoyed 10 yards apart seaward from the beads. Knowledge of the range aided in determining the speed of the approaching slick. The exact time its leading edge arrived at the beads and also the time the trailing edge passed the beads were marked on the recording tape together with the temperature at six levels.

Weather

Wind speed and direction during the observation periods were recorded by the Radio Meteorology Section at NEL, 6 miles away.

DATA

All temperature-depth series were scaled from the tape every 30 seconds, and values at the six levels were plotted and contoured in single-degree isotherms with respect to depth and time. Data for 28 hours and 4 minutes are reproduced in figures 3A to 14B, together with the times of occurrence of sea-surface slicks. These times are indicated on the figures by heavy bars at the top and vertical dashed lines. The horizontal scale is marked along the top and bottom at 5-minute intervals. Since the time increases from left to right, the vertical fluctuations, commonly referred to as internal waves are moving from right to left. The vertical scale marked on the left is depth in feet and runs from the surface to 35 feet. The 12 days of temperature structure and slicks are discussed below in chronological order.

12 June 1958

Figure 3 represents the change of temperature structure with time off Mission Beach on 12 June 1958, the first day of observations. The thermocline was stronger and sharper than on subsequent days. The range of isotherms was from 66° to 53°F. The first drop in the thermocline amounted to about 15 feet in 2 minutes. A long-duration slick (heavy band at surface) was located partly over the descending isotherm slope and partly over the narrow trough. The next vertical temperature excursion occurred 18 minutes later. It, too, was narrow compared to the wave crest. The slick occurred over the upper part of the slope.

Fifteen minutes later, a third depression passed the temperature-sensing unit. Here, the slick occurred halfway on the slope as the isotherms dipped down. The slope of the after side of the depression was steeper than that of the slick side. At 1313, the temperature structure underwent a smaller oscillation without any noticeable slick at the surface. This was followed by a narrow slick associated with a little larger depression. The next slick was weak and broken. It lasted 2 minutes and just preceded a general dip in isotherms. Small fluctuations continued, with a weak slick in the middle associated with one of the depressions. These small oscillations continued and, finally, one short one was associated with a broken or dissociated slick. The slicks were less distinct when the oscillations were small and irregular.

24 June 1958

On the second day, 24 June (fig. 4A-B), the isotherms were nearly equally spaced and extended nearly to the surface. The near-surface isotherm was 66° and the temperature near the bottom of the graph was 55° at 35 feet. The first two slicks occurred near the trough or depression in the thermocline. The next occurred on the advancing slope. The next two were over minor crests, followed by one each over a receding slope and trough. However, the next *nine* slicks occurred on the receding slope of the internal waves created by the oscillating thermocline. It appears that whenever the thermocline took a rapid descent, the slick was characteristically on the descending slope. The following two were broad, weak slicks over the forward side of the trough, and the last slick of this long period fell characteristically over the receding side of the crest.

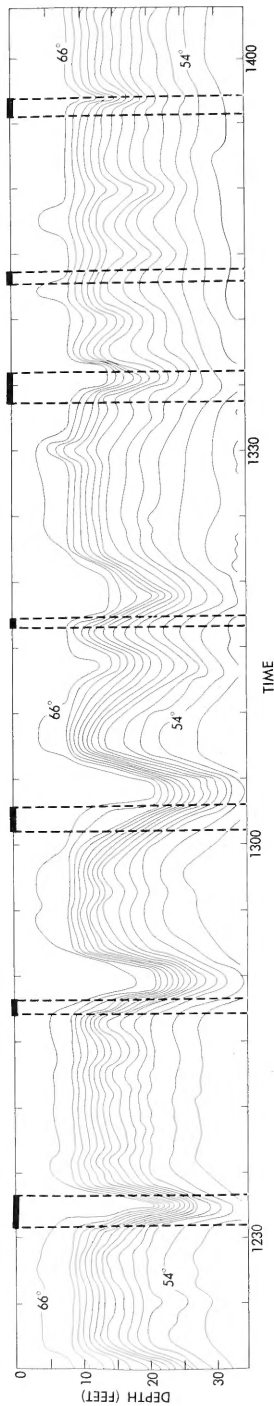
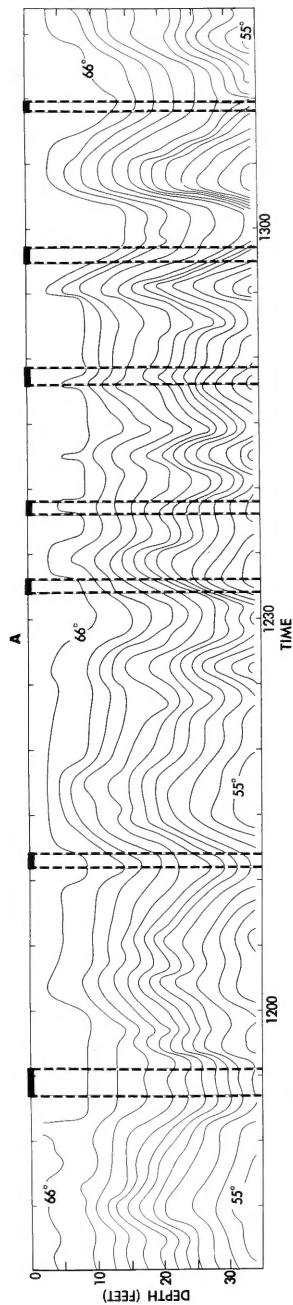


Figure 3. Temperature structure and slicks 12 June 1958.



Figures 4A, B, C. Temperature structure and slicks 24 June 1958.

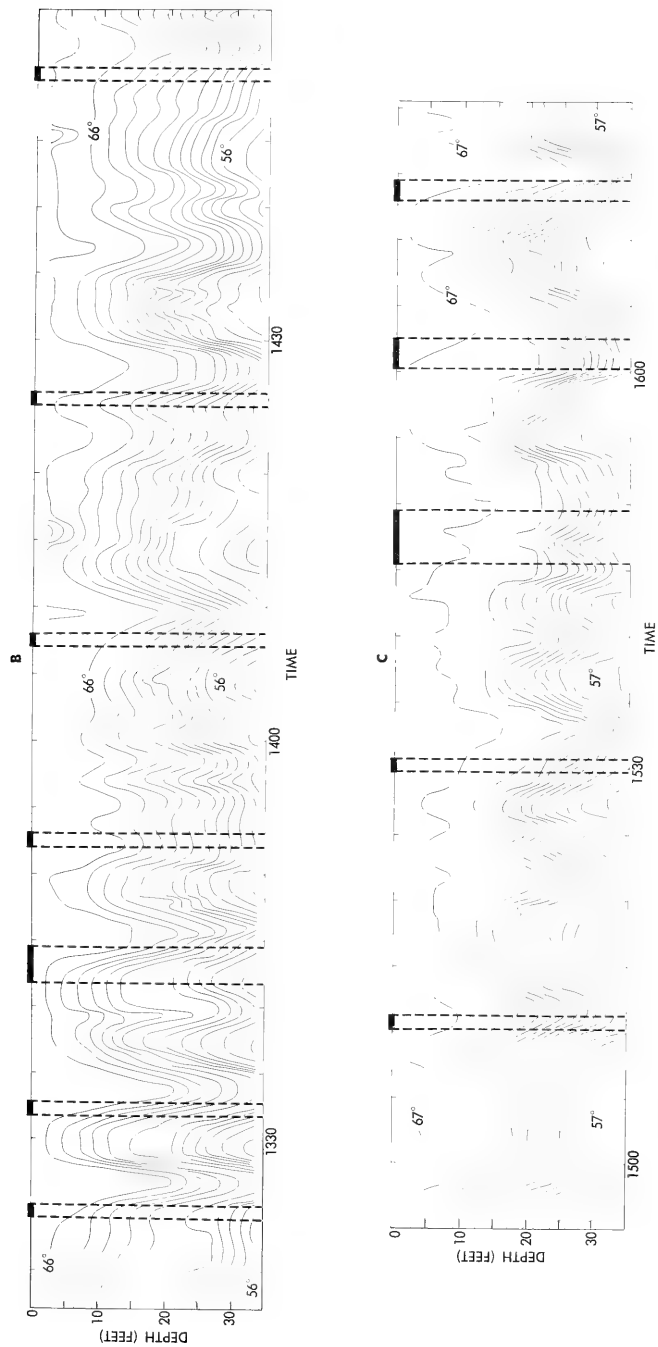


Figure 4. (Continued)

25 June 1958

The thermocline on 25 June (fig. 5A-B) was rather strong during the first half-hour, apparently descended, and became weaker in the upper 35 feet toward the end of the day's record. The vertical oscillations and slicks were quite numerous in the first half of the day, becoming less regular towards the second half. There were 22 small slicks in a period of 2 hours and 54 minutes. They occurred very close to each other and nearly all were associated with individual oscillations in the thermocline. Where there were more oscillations, there were more slicks; however, their orientation with respect to the ascent and descent of the thermocline was less consistent than on most of the other days. In nearly all cases, one slick was associated with one depression or crest. There were only one or two exceptions in which a slick was observed and a depression was not definitely associated with it.

26 June 1958

The thermocline on 26 June (fig. 6A-B) was relatively deep and strong, and its top was about 15 to 25 feet below the surface. There were many small irregularities in the thermocline. On this day, the wind was blowing from the southwest to south. Consequently, although many slicks were recorded, they were all being broken up into patches, and none were distinct glassy streaks. The first four slicks were associated with small depressions, followed by one in a broad trough. The next was over an irregular oscillating thermocline. The second half of the record, too, was made up of relatively small oscillations (about 5 feet and 5 minutes). The second and third slicks in this half appeared over a small lowering of the thermocline. The next three were associated with a lowering of the thermocline most of which descended below 35 feet at 1355. The last slick was still broken and occurred at a time when the thermocline was descending. This irregular relation of slicks to oscillations in the thermocline was caused by the large angle between the direction of the wind and that of the internal waves.

8 July 1958

On 8 July (fig. 7) the 1° isotherms were a little more compact, that is, the vertical temperature gradient was relatively stronger and nearer the surface than on some of the previous days. The isotherms fluctuated rather widely throughout the day, and at no time was the thermocline at a constant level. The first slick occurred just before a trough and on the steepest part of the descent. The second and third slicks were likewise associated with a descending isotherm. These were followed 20 minutes later by a series of nearly equally spaced, vertical oscillations in the thermocline. Most oscillations had rather weak slicks associated with them. Some did not fall exactly on the steepest part of the waves, but instead occurred higher up, almost at the crest. Finally, there was a slick near the end of the day's record, and a depression appeared to be starting as the record ended.

9 July 1958

On 9 July (fig. 8) the thermocline was near the surface but rather weak compared to other days. Only four slicks were observed in a period of over 1½ hours. The first slick occurred on the descending slope. The second slick, after a period of relative inactivity in the thermocline, also occurred on the descending slope. The third slick, too, was over a descending slope. The last one of this day was on a gradual descending slope.

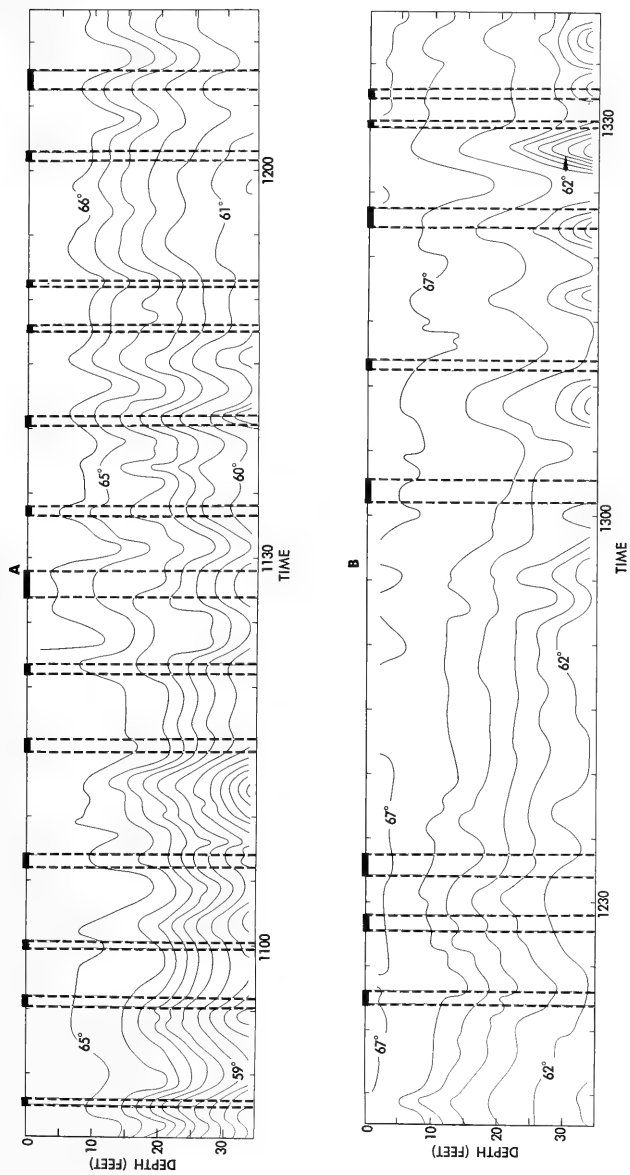


Figure 5A, B. Temperature structure and slicks 25 June 1958.

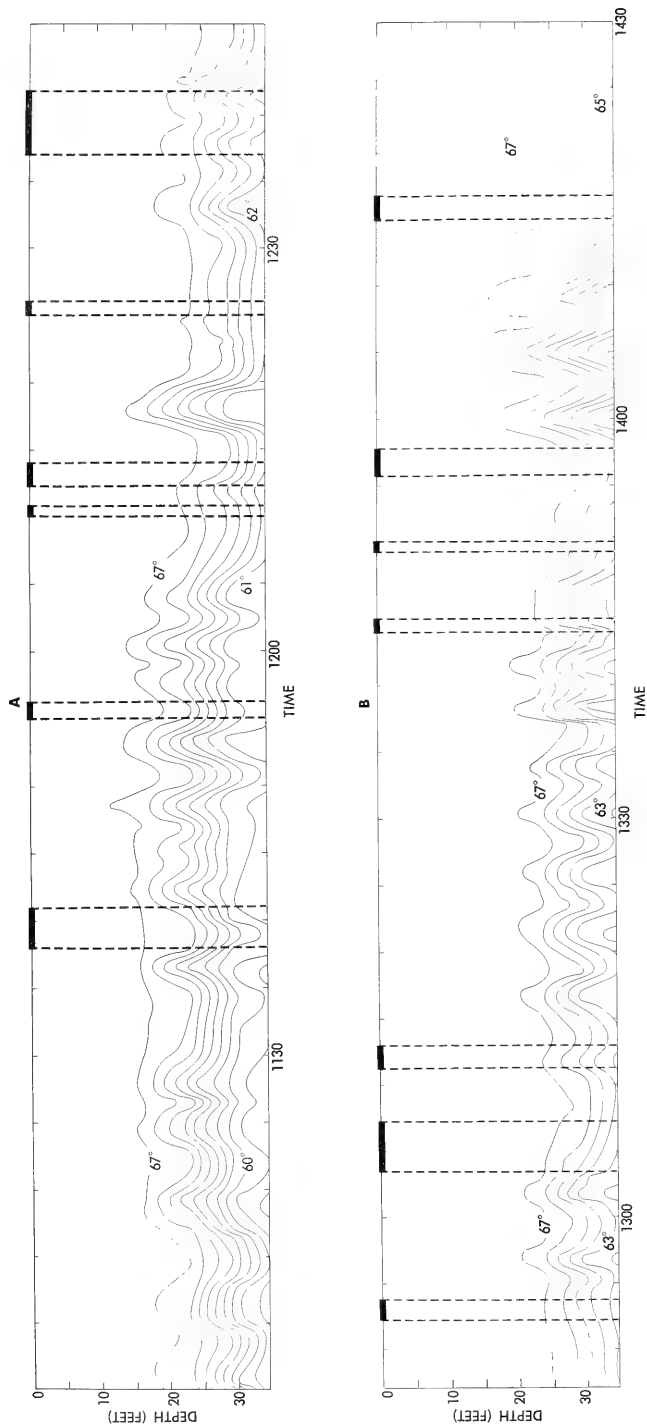


Figure 6A, B. Temperature structure and slicks 26 June 1958.

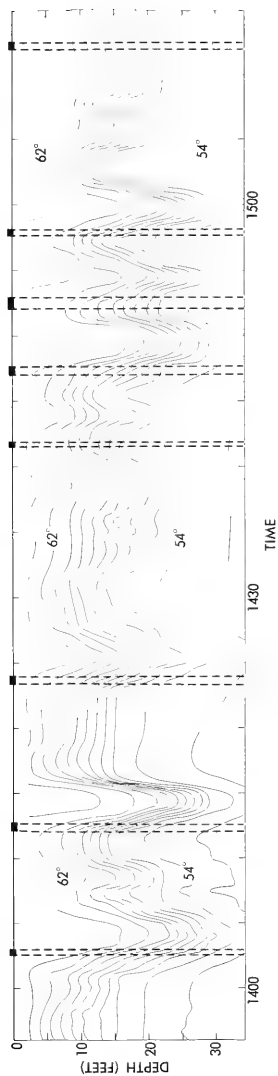


Figure 7. Temperature structure and slicks 8 July 1958.

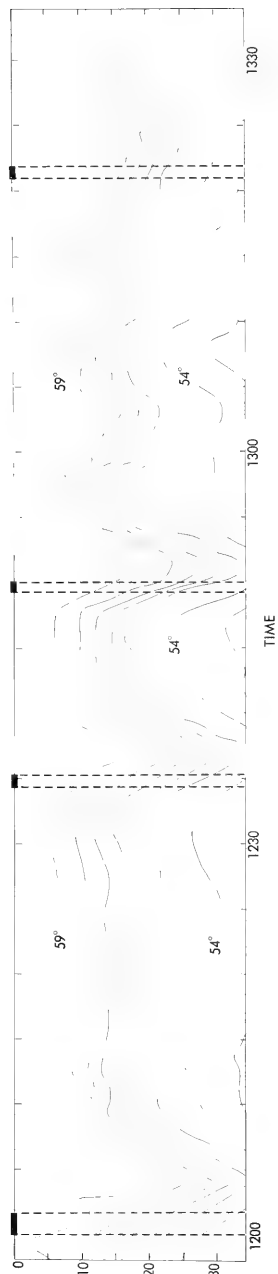


Figure 8. Temperature structure and slicks 9 July 1958.

23 July 1958

The temperature record for 23 July (fig. 9) started with a shallow gradient. The first slick was on the wave slope or descending thermocline, similar to most of the preceding examples. However, the second slick was an exception. It preceded the depression with which it must have been associated by 5 minutes. Just why this slick was displaced from the depression is not known. One different feature was the colder water which had protruded upward. Following this large rapid fluctuation, the vertical motion was more uniform, with only one minor vertical shift in the thermocline apparent. The next major change in the vertical excursion of the thermocline 18 minutes later amounted to 17 feet. Here, the location of the slick was halfway down the slope. Finally, the last slick fell on the center of the descending thermocline. This lowering of the temperature isolines amounted to about 18 feet. It is evident from these examples that great changes in depth of isotherms can occur in a short time of 1 or 2 minutes.

24 July 1958

On 24 July (fig. 10) the thermocline extended up to the surface. It was rather uniform from the surface to 35 feet throughout the day's observation. At the beginning, the temperature range was from 68° to 56° . The first slick occurred just before a broad, wide depression in the thermocline. The slick associated with the depression was on the gradual descending slope. The advancing wave slope was steeper than the receding one. The second slick was found over the descending slope, falling off into a broad depression 10 feet deep. Apart from one small oscillation which had no slick, the following six major oscillations each had an associated slick varying in position from over the crest to the lower part of the receding slope. The oscillations for this day were broader than for the preceding two days.

25 July 1958

On 25 July (fig. 11A-B) the thermocline was strong and near the surface. The first slick occurred just before the first depression, that is, on the receding slope. The second slick, after numerous minor irregularities in the thermocline, occurred near a crest of one of the minor irregularities. Numerous minor irregularities in the thermocline occurred during the first hour of this day. The only major slick was the first one. The next slick followed a small rise in the thermocline, and was succeeded by a slick high on the slope of a sharp drop in the thermocline. The record ended too early to notice whether any slicks were associated with the last large wave.

6 August 1958

On 6 August (fig. 12) the thermocline also extended to the surface. The first two slicks were on the receding side of a wave crest and over a depression in the thermocline. The third, fourth, and fifth slicks occurred after minor crests, but all three were on the receding side. The sixth and seventh slicks occurred on the receding side of the major depressions. The seventh and eighth slicks also fell on the receding side of the small internal wave crests. When the thermocline is near the surface, as it was on this day, the slicks appear to be more uniform in relation to the thermocline even though the oscillations are not great or very steep.

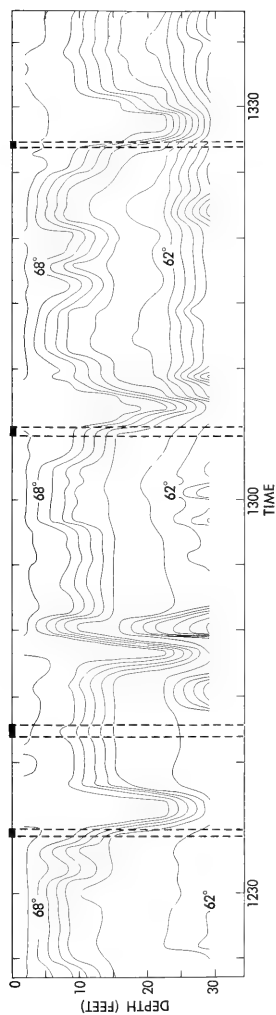


Figure 9. Temperature structure and slicks 23 July 1958.

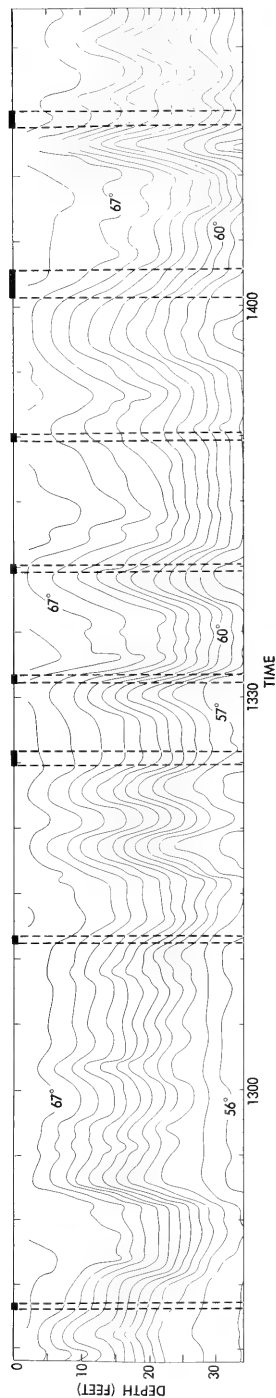


Figure 10. Temperature structure and slicks 24 July 1958.

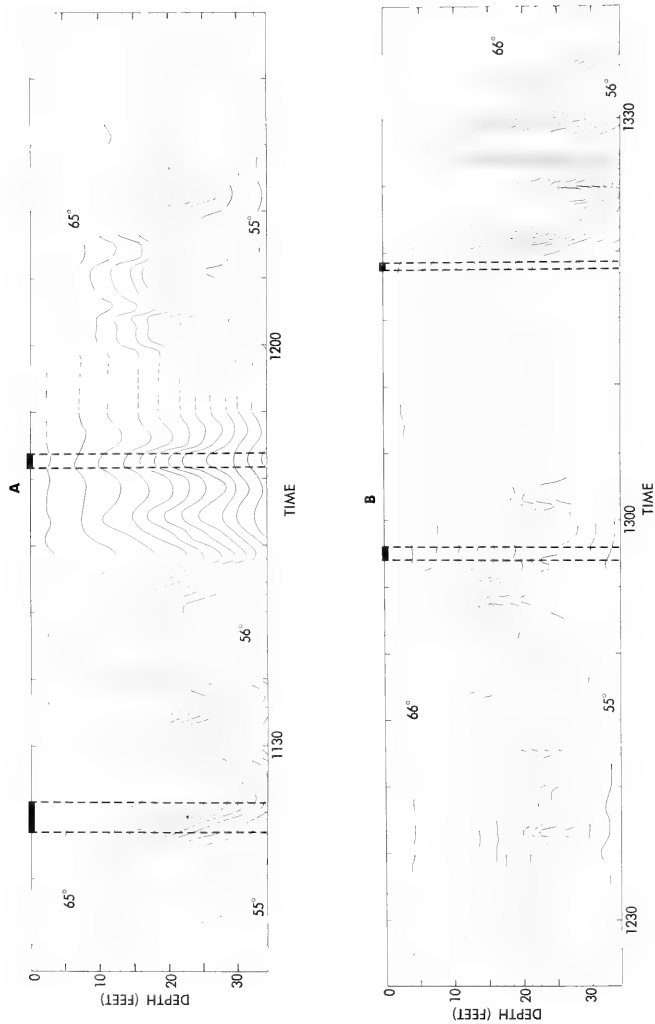


Figure 11A. B. Temperature structure and slicks 25 July 1958.

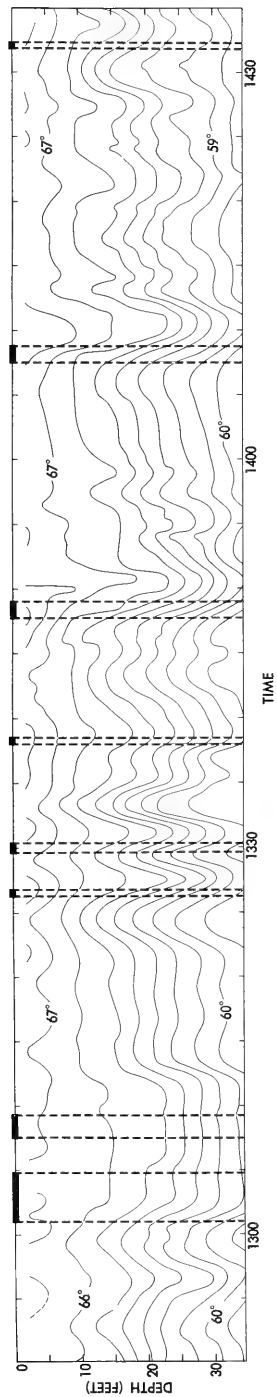
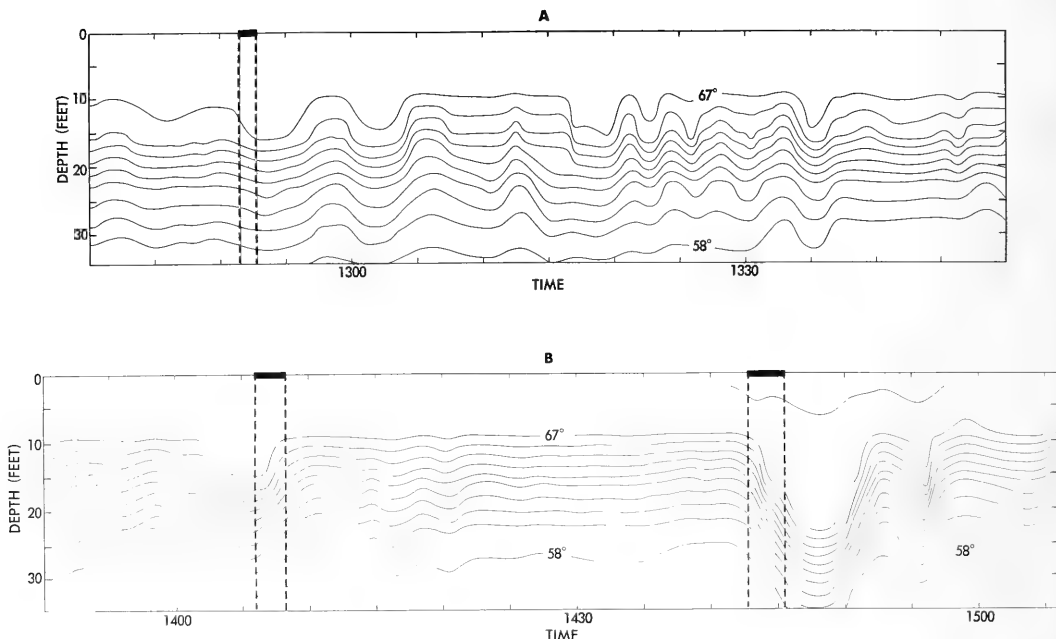


Figure 12. Temperature structure and slicks 6 August 1958.

7 August 1958

On 7 August (fig. 13) the water was mixed near the surface, but a strong thermocline remained at 10 feet throughout the day's observations. A minor depression occurred about 10 minutes after the start of the record. A slick occurred just before the trough. For over an hour after this, only minor irregularities existed in this relatively constant-depth thermocline. The second significant depression of only a few feet occurred with a slick on the ascending side of the depression. The only major depression of the day occurred toward the end with a strong slick on the descending slope. The period towards the end of the record probably features the flattest thermocline yet experienced in this region. For nearly 30 minutes, the major part of the thermocline varied less than plus or minus 2 feet.



Figures 13A, B. Temperature structure and slicks 7 August 1958.

8 August 1958

On 8 August (fig. 14A-B) the top of the thermocline was within a very few feet of the surface. The observation period started with two oscillations with a slick on the receding side of the second crest. The second slick was on an ascending slope, and the third, a very small one, on a descending slope. The fourth was in the middle of a descending slope falling off into a large depression. The fifth slick was high on the slope of a very deep trough and, then, 35 minutes later occurred the last slick of this day which was on the descending slope of the last major trough. Actually, on this day, there were only four rapidly descending slopes, all of which had associated slicks in the descending portion. The remaining slicks were related to minor irregularities in the thermocline.

The preceding examples of slicks and vertical oscillations of the thermocline show that, whenever there is an appreciable dip in the thermocline, a slick is present and usually occurs over the slope which precedes the depression. This relationship will be discussed later.

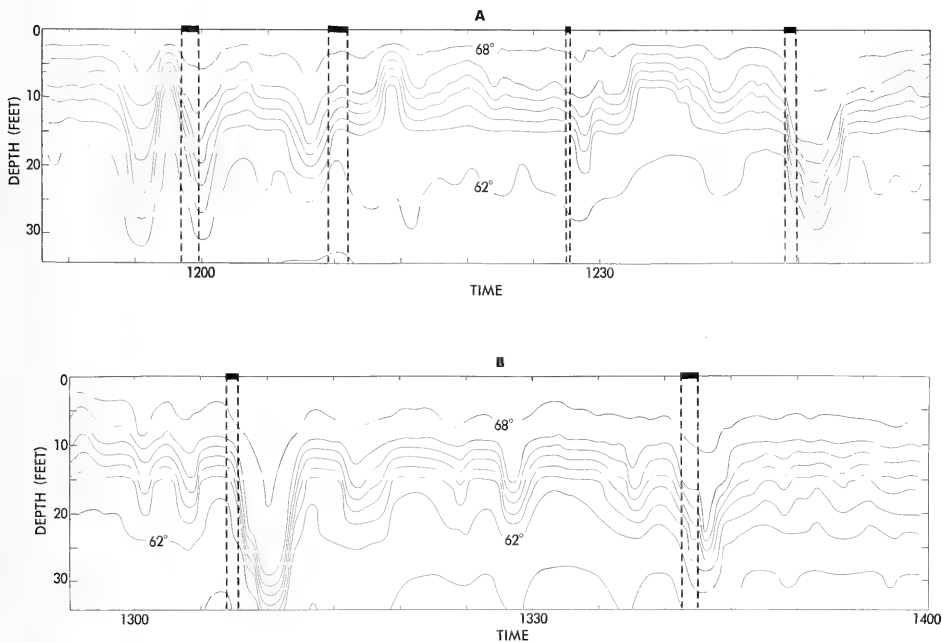


Figure 14A, B. Temperature structure and slicks 8 August 1958.

SUMMARY OF DATA AND DISCUSSION

Oscillations

The isotherms fluctuated vertically with time during all the observations (fig. 3-14). The height of the fluctuation was not consistent over any great length of time. Sometimes patterns appeared, but these were soon changed or interrupted by other patterns. When one isotherm in the thermocline dipped, nearly all the others did too. This was especially true when major wave-type cycles were present. The shapes of the internal waves varied, but they were generally symmetrical about the crests; in many waves, the advancing face of the crest was steeper than the receding face (fig. 3, 4, 6A, 7, 8, 9, 10, 11B, 13B, and 14).

Slicks

Slicks were present about 10 per cent of the time. During the periods of operation 105 slicks were recorded. The duration of any single slick, as it passed any point, was from 0.35 to 5 minutes, averaging 1.3 minutes.

Wave Height

The magnitude of the vertical fluctuations was generally inversely proportional to the gradients through which they protruded (fig. 9, 10, and 14B). Smaller fluctuations were always present.

The maximum daily vertical migration of an isotherm in the middle of the thermocline, during the periods of investigation and in the upper 35 feet, was 22 feet on 22 July (fig. 14B).

The frequency distribution of heights of the shallow internal waves of each day is shown by the total height of the histogram columns in figure 15. Only waves greater than 2 feet were considered since the smaller ones are probably only random fluctuations. Although these were for different periods of time, as noted, the relative distribution can be compared for the different days. During June, the wave heights for the period of observation tended to be smaller than those for July and August.

Wave Heights and Slicks

On the same figure, the histogram columns are shown in either dark or light shading. The dark shading represents internal waves which were associated with a sea surface slick, and the light shading internal waves without slicks. All the largest waves, that is, with heights 16 feet or greater, had slicks associated with them.

In a time of 28 hours and 4 minutes, spread over 12 days, there were 169 waves greater than 2 feet. A composite distribution of the internal heights of these waves is shown in figure 16. Fifty per cent of the waves considered had heights of 7.2 feet or greater. The shading of this figure is also indicative of waves with slicks and waves without slicks.

Wave Period

The frequency distribution of the durations of these 169 internal waves by days in 3-minute intervals is given in figure 17 (waves with periods less than 2 minutes were neglected). The relation of slicks to wave period is also shown in this figure by the darker part of the columns.

A summation of the 12 days' data is given in figure 18. Fifty per cent of all waves longer than 2 minutes had periods greater than 7.6 minutes.

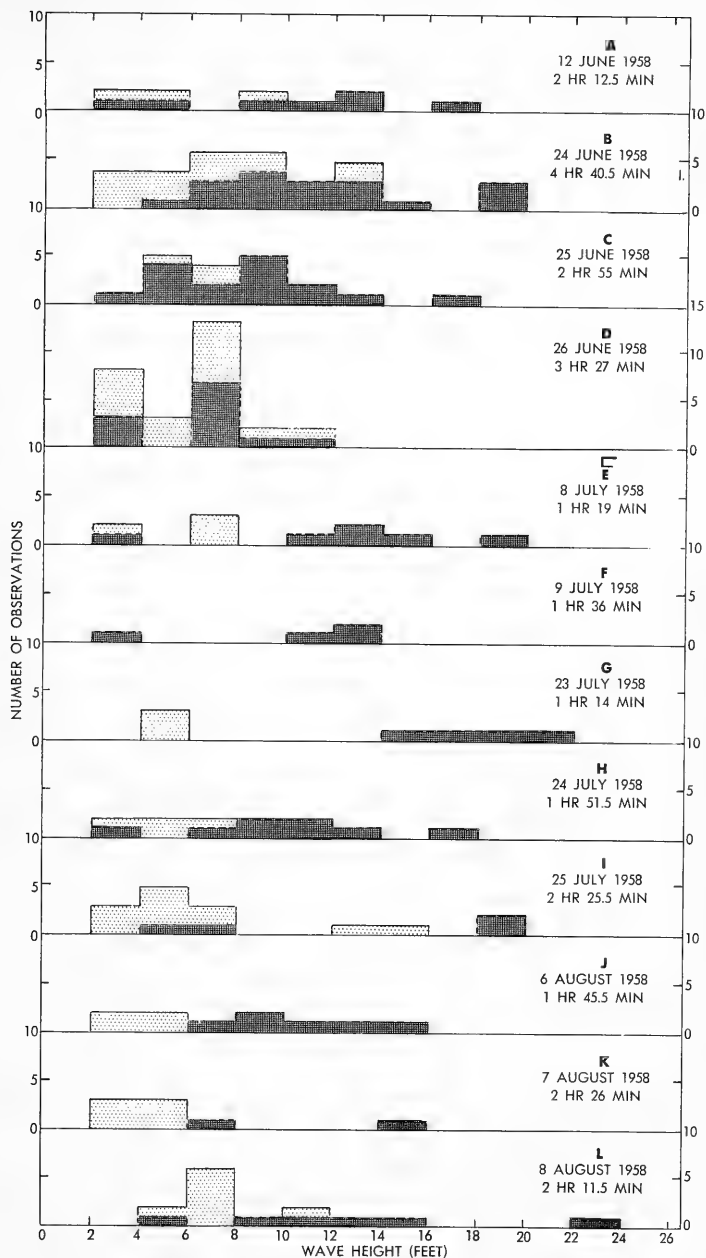


Figure 15. Frequency distribution of all internal wave heights over 2 feet (light and dark shading) and internal wave heights with associated slicks (dark shading) for each of the 12 days during which observations were made.

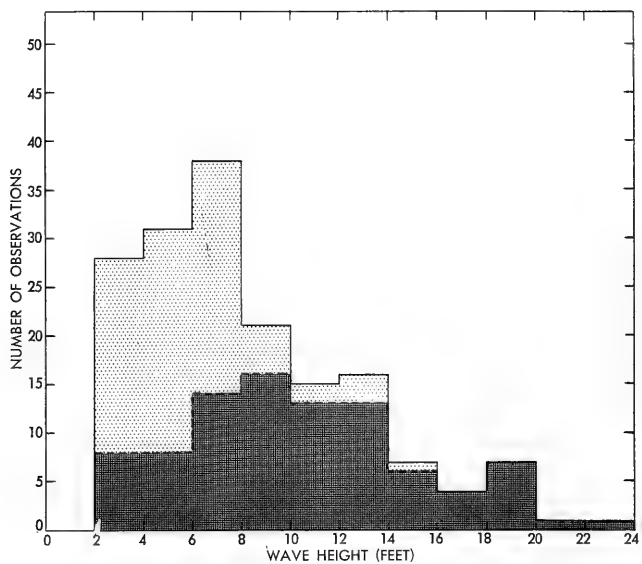


Figure 16. Composite frequency distribution of internal wave heights over 2 feet (light and dark shading) and internal wave heights with associated slicks (dark shading) for all data.

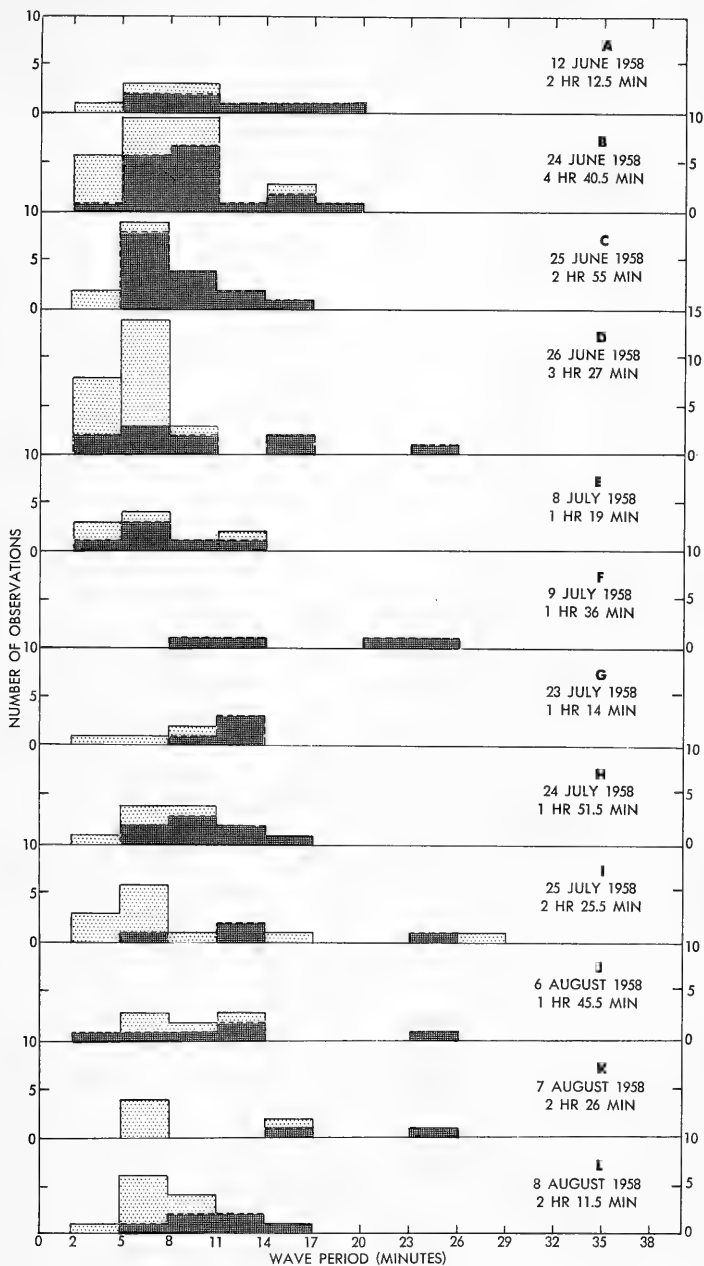


Figure 17. Frequency distribution of all internal wave periods over 2 seconds (light and dark) and internal wave periods with associated slicks (dark shading) for each of the 12 days during which observations were made.

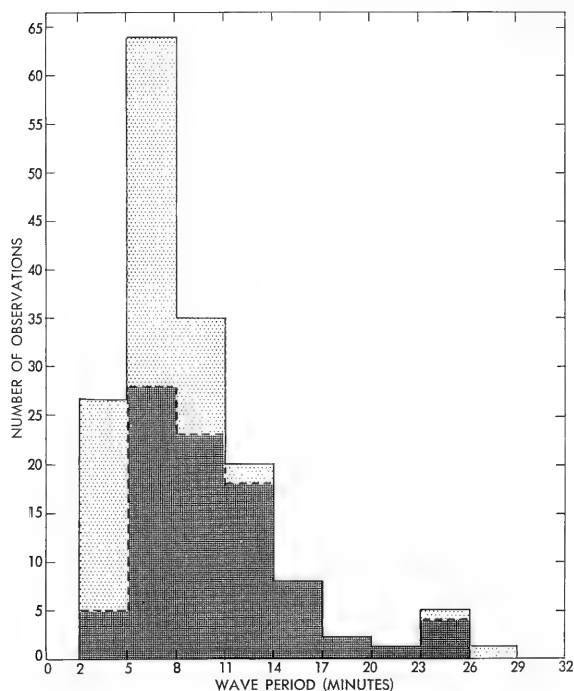


Figure 18. Composite frequency distribution of internal wave periods over 2 seconds (light and dark shading) and internal wave periods with associated internal waves (dark shading) for all data.

Wave Periods and Slicks

Slicks were generally associated with the longer-period waves, but were absent from the longest-period wave. Slicks are more related to wave height than to wave period for the depths of thermoclines and water observed.

From observations of wave speed, an estimate of wavelength can be made. It was found by use of range markers that the speed of definite slicks was 0.31 knot. Since the internal wave travels at the same rate as the slick, the same speed applies to internal waves. A wave of average period 7.6 minutes would be 236 feet long.

Occurrence of Slicks

From the foregoing it appears that the occurrence of visible slicks depends on several factors. In addition to proper wind, lighting, and sufficient organic matter on water, slick formation depends on the nature of the internal waves. The concentration of the surface film depends on the interrelation of internal wave height and period. In addition the average depth of the internal wave and its relation to the depth of water will also influence the type of circulation and thus the formation of slicks.

Position of Slicks with Respect to Internal Waves

Sometimes, the surface slick was over the trough of the depression in the thermocline; at other times, the slick wandered to a position nearly over the crest of the wave. However, for 85 out of 105 cases shown in figures 3 to 14, the slick was on the descending thermocline, somewhere between the crest and following trough. The cause of this relationship is believed to be the water circulation created by internal waves.

Water Motion

The circulation in slicks may be deduced by several means: (1) The concentration in lines or patches of film at the surface indicates a motion towards the patch from one or both sides; otherwise, the film would spread out and break up. (2) From the vertical structure, the lowering of the thermocline is indicative of downward motion. Also, maintenance of a depressed thermocline requires a force towards this zone. (3) The accumulation of turbid material in zones implies either a downward motion from the surface, where turbid material frequently collects, or an upward motion from the thermocline, which is frequently another source of turbidity. It is possible that in regions of upward motion, some organic material is brought to the surface where the action of air or change in the properties of the organism will lower its density and cause it to resist the downward circulation under the slicks.

Current drags, on the other hand, sometimes drifted through a slick; on other occasions, they moved towards a slick and aligned themselves in it. This variation is indicative of different water movements associated with slicks.

Distortion of a straight line made on the water surface by sea marker dye showed that, in addition to vertical motion normal to the slick, there is a flow in or parallel to the longer axis of some slicks.

Vertical movement was once investigated by means of dye marker. Dropping the dye marker vertically and observing the horizontal distortion showed that a shearing stress existed in the thermocline.

From time-lapse films of the sea surface taken at Mission Beach, La Jolla, and San Diego Bay, the motion of the surface was studied. In all cases, the sea slicks moved on-shore at speeds of 0.11 to 0.6 knot, corresponding to the average of 0.31 knot measured from the ship with range markers. The shape of slicks varied as they moved shoreward and the slicks appeared to refract as they moved into shallower water. In the presence of currents in San Diego Bay, slicks moved with the direction of flow and were predominant at water type boundaries.

In the sea, internal waves are believed to take the form of progressive waves. The nature of progressive waves between two liquids of different densities is given by Lamb.⁹

The vertical displacement at the interface of a two-layer density system, densities ρ and ρ' is given by

$$\eta = a \cos (kx - \sigma t)$$

The horizontal velocity of flow, u' in the upper layer is

$$u' = -(a/h') c \cos (kx - \sigma t)$$

where

h' = average thickness of the upper layer

a = amplitude of wave at interface

c = wave velocity at interface

The circulation of a simple progressive wave is shown in figure 19. The fine arrows represent the trajectories of particles.

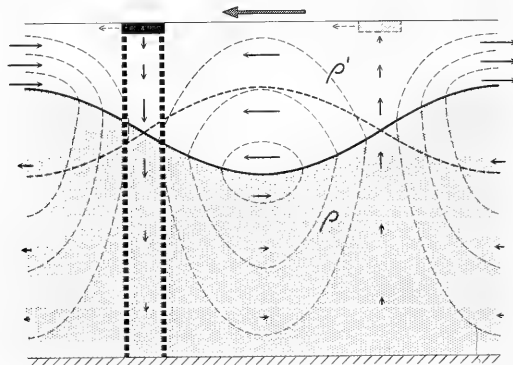


Figure 19. Simple progressive internal wave between water of two densities ρ and ρ' . The large arrow at the top shows the direction of the wave. The water motion trajectories are shown by the small arrows and the normal location of the slick by the heavy bar.

The significant motion is a surface convergence over the trailing slope of the internal wave. Although the maximum expansion of the surface layer is over the trough, the slicks are normally found at the active convergence zone.

Wind Effect

Since the wind in most cases was westerly, it is possible that the slick film was displaced in its direction, that is, away from the trough towards the crest. On one day, 26 June, the wind was from 205 to 250 degrees or southwesterly, and the slicks did not bear a consistent relation to the waves. However, wind speeds of 2 to 5 miles per hour were required to make the slicks stand out in contrast to the rougher adjacent water.

In the southern California area, the winds during the day are predominantly from the sea towards shore, that is, in the same direction as the internal wave; therefore, some consistency can be expected whether or not the slick is set shoreward by the wind.

CONCLUSIONS

1. The depth of isotherms in the shallow summer thermocline fluctuates virtually all the time. At Mission Beach, California, of the significant vertical oscillations of a central isotherm in the thermocline, half were greater than 7.2 feet and half had periods greater than 7.6 seconds. Because the internal waves were refracted, they usually proceeded in a general shoreward direction at the measurement site where they had an average speed of 0.31 knot.

2. Every large internal wave of height greater than 14 feet had a sea surface slick associated with it for the thermocline depths observed.

3. In accordance with wave motion theory of simple internal waves, an active convergence circulation occurs over the descending slope of an internal wave. In 85 cases out of 105, the slick occurred between the crest and the following trough. The relationship was sufficiently reliable to provide an approximate prediction of the subsurface thermal topography at the measurement site from a knowledge of the distribution and movement of the sea surface slicks.

RECOMMENDATIONS

Continue the general study of the near-shore and near-surface environmental characteristics which affect acoustic transmission. Give special emphasis to long duration waves and to the geographical distribution of internal waves. Study acoustical transmission through internal waves.

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APPENDIX: MULTIPLE CHANNEL TEMPERATURE RECORDING UNIT

General

A sixteen-channel temperature sensing unit was developed and has been used at NEL for several years. It consists essentially of thermistor beads cast in plastic and attached to electric leads. The leads and beads are part of a bridge circuit which feeds a recording-type potentiometer. The recorder prints numbered points consecutively from 1 to 16 on a power-driven strip chart, the location of each number indicating a particular temperature. In normal operation, a full cycle of recordings requires approximately half a minute. This time varies, depending upon the range of temperatures to be recorded. Since the temperatures measured are of sea water near the surface, they may vary considerably as the elements go through the thermocline. However, the sequence of points will change in the same direction, from hot to cold as the depth increases and in reverse as it decreases. Thus, the recording head has to travel a small distance between each printing, enabling it to run through a full cycle rapidly.

The instrument was designed to measure temperatures in the range from 28°F to 90°F. The strip chart employed is 11 inches in width, divided into 150 units. Hence, for the accuracy required (at least 0.1°F), we divided the full range into 10 subranges, in which each 11-inch width of tape covers 7° to 7.5°F. The subranges overlap each other by at least half a degree. This enables reading of the chart to better than 0.02°F.

A Brown Recording Potentiometer (Brown Instrument Co.) was built into a single unit with the necessary bridge and switching elements, the whole weighing approximately 200 lb. This unit may be transported and mounted on shipboard (fig. A1).

On the face of the unit are mounted sixteen jacks to accommodate leads of the sixteen sensing elements, sixteen range switches, a voltmeter, and a rheostat for maintaining constant current during operation.

The sensing elements and thermistor beads are mounted at the ends of cables of appropriate lengths, so that they may be lowered to whatever depth is desired. These cables are plugged into the jacks on the recorder, placing their resistances across one arm of the bridge circuit for the temperature range under measurement.

Design of Temperature Measuring Unit

The thermistor bead was chosen as the sensing element for use with this recorder because of its very great change in resistance with temperature change. Specifically, the Western Electric 14B and Veco 32A-1 thermistors change from approximately 2300 to 3500 ohms over the temperature range of 70° to 52°F. The great disadvantage of thermistor beads is their nonlinearity of response, but this was obviated to a great extent (1) by designing the associated circuits so that each temperature range measured was small and, hence, the resistance change over that range nearly linear, and (2) by calibrating for each range at closely spaced points.

The beads are enclosed in glass rods averaging 1/16 inch in diameter and about 2 inches in length. The bead, itself, is at one end, and the leads pass through the length of the glass and emerge at the other end. For underwater use, the beads must be protected electrically from the water and mechanically from physical

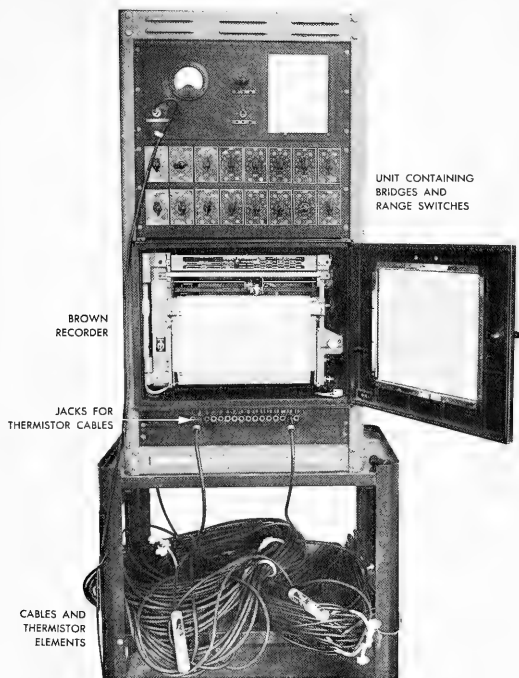


Figure A1. Sixteen-channel temperature measuring unit.

contact, as they are extremely fragile. They were therefore cast in a cylinder formed by pouring a plastic, Furnane 502, Epocast, with General Mills 125 Versamid, into a 1-inch outside diameter Lucite tube. The thermistor beads in parallel, their compensating resistor, and the three-conductor electrical cable were mounted in the cylinder. Figure A2 shows the assembled unit and its construction. The sensing beads project 1/8 inch from the end of the cylinder and are protected by two hoops of 1/16-inch stainless steel wire embedded in the plastic. The plastic bonds with the glass covering of the bead and the outer insulation of the electrical cable to form a watertight unit (fig. A2 shows details of mounting). The outer end of the cable has a three-contact plug for insertion in a jack on the recorder panel. The plastic bonds well with almost all materials, is simple to pour having only two ingredients, and does not deteriorate appreciably. It can be poured into a Lucite tube directly, eliminating the necessity for special molds.

A simple Wheatstone bridge circuit was employed (fig. A3) in which the resistances R_1 and R_2 are fixed; R_3 consists of ten resistors arranged so that any one of them may be switched into the circuit. The values of these resistors are selected

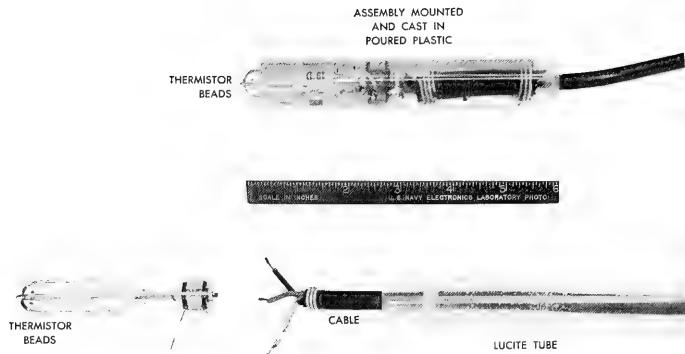


Figure A2. Thermistor bead mountings.

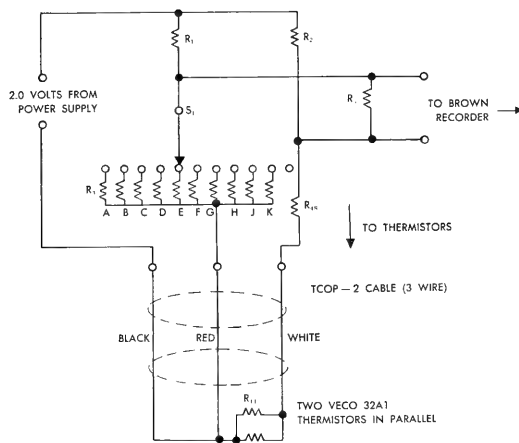


Figure A3. Thermistor bead circuit.

Resistance values are:

$R_1 = R_2 = 2500 \, \Omega$	$R_3G = 1874 \, \Omega$
$R_3A = 3935 \, \Omega$	$R_3H = 1670 \, \Omega$
$R_3B = 3435 \, \Omega$	$R_3J = 1534 \, \Omega$
$R_3C = 3020 \, \Omega$	$R_3K = 1400 \, \Omega$
$R_3D = 2660 \, \Omega$	$R_4S = 408 \, \Omega$
$R_3E = 2348 \, \Omega$	$R_4T = 1940 \, \Omega$
$R_3F = 2094 \, \Omega$	$R_5 = 67 \, \Omega$

so that each one will bring the bridge into balance in one of the ten temperature ranges covered by the instrument. R_4 is made up of the resistance of two thermistor beads in parallel, R_{4T} in series with R_{4S} (field resistor). The circuit is completed by the resistor R_5 in parallel with the leads to the recorder. R_{4S} and R_5 compensate for the difference in voltage output at high and low temperatures, thus making each subrange approximately the same, namely, 7.0° to 7.5°F , from 28.0° to 90°F ; each subrange overlaps the next by about 0.5°F .

Figure A3 indicates the multiple bridge which handles one channel only, and shows how the subranges are put in the circuit to handle the full range from 28° to 90°F . The eleventh contact is open to put that channel out of use.

In the instrument, there are fifteen more bridges assembled similarly, one for each channel, there being an automatic switching device in the recorder for inserting channels 1 to 16 into the potentiometer circuit consecutively.

The third conductor in the cable is essential to eliminate error due to changing resistance in the leads caused by change in temperature of the surrounding water.

The switch S_1 is a rotary, 11-contact type, by means of which the desired temperature subrange may be chosen from A to K . As the recorder prints, the specific bridge having been brought into balance with the potentiometer, S_1 is moved to contact the next bridge circuit until it reaches K , and then a new cycle begins at A .

The values for R_{4S} and R_{4T} must be calculated for each bead assembly, as their function is to compensate for the differences in value of the resistances of the individual beads.

The rotary switches (S_1) have copper contact points with a multileaf spring contactor mounted on a ceramic base. Ten of these contacts are connected, one to each of the range resistors; the eleventh opens the arm of the bridge. These contacts must be kept clean, as any extraneous resistance will introduce error in the recorder reading.

Associated with the bridge assembly is a source of potential, consisting of two standard dry cells, a voltmeter, and potentiometer. These enable the operator to maintain a constant potential across the bridge at all times, which is essential to the accuracy of its operation.

Recording Potentiometer

All the above circuitry is contained in the upper part of a cabinet, the lower part of which houses the recording potentiometer (fig. A4).

The recorder employed is a Brown Recording Potentiometer No. 153-62, having a full-scale travel time of $4\frac{1}{2}$ seconds. Its sensitivity is $\frac{1}{4}$ per cent of scale span, at 0.019 millivolts for spans less than 8 millivolts. The record is printed on a strip chart of 11 inches recording width, having 150 divisions. The chart is driven past the printing head by an electric motor, at a speed determined by the gear ratio of the drive which may be altered to give any speed from 2 inches/hour to 480 inches/hour. Usually, a speed of 22.5 inches/hour was satisfactory (fig. A5).

In this system, a slide wire potentiometer is driven by a screw mechanism to balance the applied potential against a self-contained potential. When balance is achieved, the printing wheel automatically prints a cross and a number, the number designating the channel being scanned at the moment. The circuit then automatically switches to the next channel, and the process repeats with the next consecutive number coming up on the printing wheel. The complete scanning of

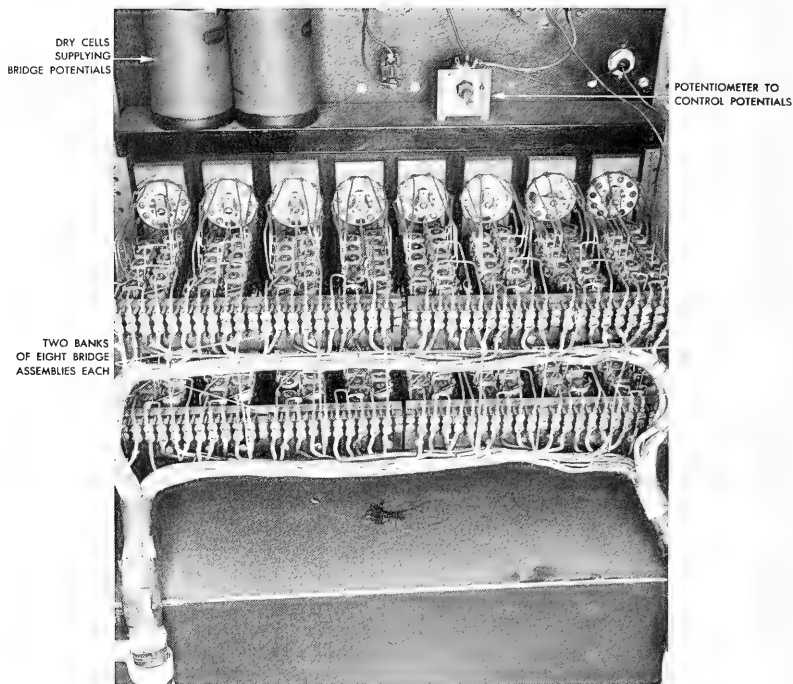


Figure A4. Bridge assembly for sixteen-channel temperature measuring unit.

the sixteen channels ordinarily requires about a half a minute, but the time depends on the differences in temperature of the points being measured. It is conceivable that, if each alternate point of temperature were at opposite ends of the range thus forcing the recorder bead to travel the full scale for each printing, the time for a full cycle would be 72 seconds. This, however, would be an extreme case.

The unbalance in the bridges is caused by changing resistance in R_4 brought about by the changing temperature of the thermistor beads which are part of that arm. Thus, potential can be translated into temperature, by means of previous calibration of the recorder against known temperatures.

The difference of potential between the bridge arms and the potentiometer is amplified by a Brown amplifier, so that it can drive a servomechanism. The servo moves the sliding contact in the potentiometer circuit until the applied potential from the thermistor bridge and the reference potential are equal. The reference potential is supplied by a dry cell whose voltage is standardized automatically

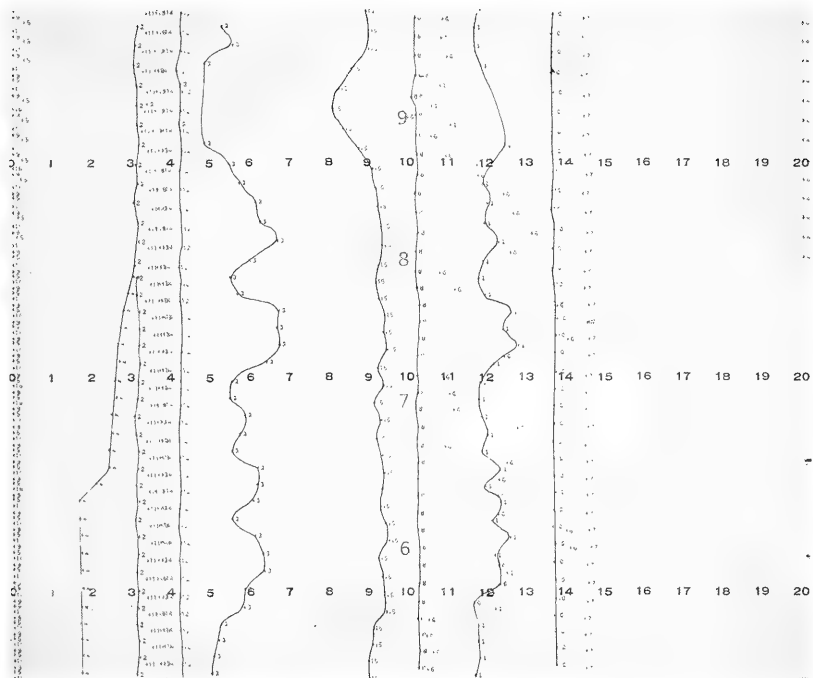


Figure A5. Example of time series and temperature readings on recorder tape.

every 15 minutes against that of a standard cell incorporated in the instrument. Standardization may also be done at will by the operator, and is always done at the beginning of each run. Thus, the amplifier-servo system acts essentially as a null detector galvanometer.

Accuracy

The original specifications for the circuits in this instrument called for an accuracy of $\pm 0.1^\circ\text{F}$. The Fahrenheit scale is used so that the recordings may be compared directly with bathythermograph measurements which are made simultaneously. It was found that, by careful matching of the thermistor beads and compensating resistors and by accurate calibration of the beads over each sub-range, an even higher degree of accuracy is attained, as can be seen in figure A6, which is a reproduction of actual records made with two beads held at two constant known temperatures.

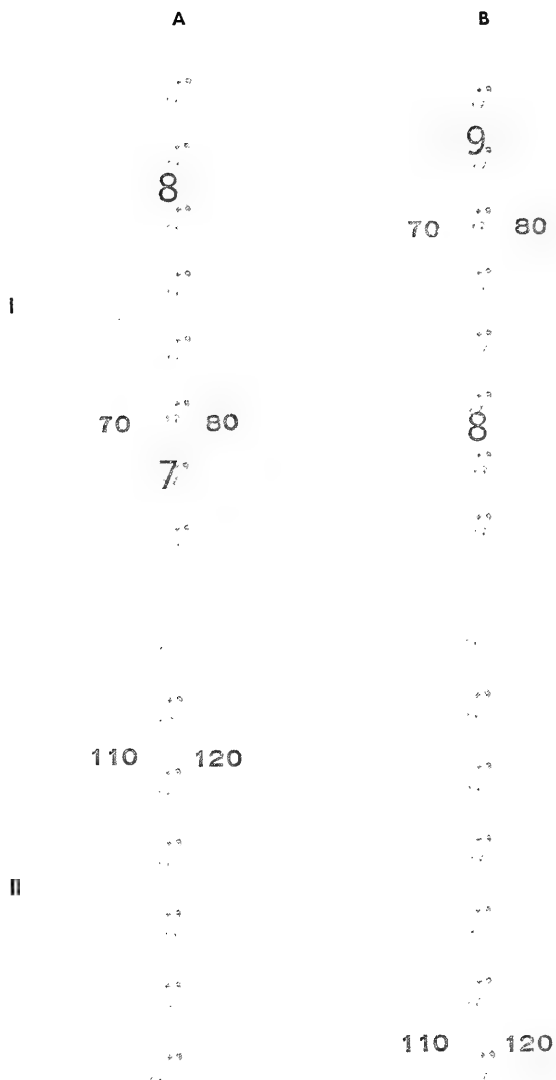


Figure A6. Example of repeated temperature recordings of 75° on IA and IB, and 70° on IIA and IIB.

In *A* of this illustration, the calibration tank was held at a constant temperature of $75.00^{\circ}\text{F} \pm 0.005^{\circ}$ while recording I was made, then lowered to 70.00°F when recording II was made. This procedure was repeated on a subsequent day to determine reproducibility. The later recordings are shown in *B* of this illustration.

The records show that at the 75° level (zero or reference level) channel 9 actually reads 76.0 units for the first day and 75.2 units for the second day. Two units on the chart measure 0.1°F . Thus, the chart records with no error on each day but with a difference of 0.04° between the two days. Channel 7 reads 75.0 units the first day and 74.8 high and 74.4 low on the second day, a minimum difference of 0.01° and a maximum difference of 0.03° between the two days, and of 0.02° in this particular run.

At the 70° level, on the first day, channel 7 records a maximum 114.8 and a minimum 113.5 units, i. e., a difference of 0.06°F , and channel 9, 115.2 and 115.0 units, a difference of 0.01° . On the second day, channel 7 reads 114.8 and 113.8, maximum and minimum, a difference of 1 unit or 0.05° , while channel 9 reads 115.2 and 115.0, 0.2 unit or 0.01° again. The maximum difference between the two days' runs is no greater than this. Thus, the specified accuracy of $\pm 0.1^{\circ}\text{F}$ is well attained.

Actually, only one or two readings were at the extremes, the majority falling within the limits of $\pm 0.02^{\circ}$.

The maintenance of an absolutely constant voltage to the bridge circuits is extremely important for accuracy. As an example, the indicating needle of the voltmeter measuring this potential can be on the indicated mark but not quite centered on it, resulting in an error of 0.02°F . The voltage must be readjusted whenever the operator changes any of the ranges.

Although the multichannel recorder can be used to record sixteen separate channels, it is often used for eight to four channels in which case the wiring is rearranged so that one bead will actuate more than one channel. In this way, the rate of recording each individual temperature is increased several fold.

This unit has been used for ten years. Some temperature recordings have been made in the Arctic and others in the tropics. It is sufficiently reliable to be left unattended for hours, with an attached timing device marking the tape every minute. Maintenance has been minimal and the entire system has proved highly satisfactory.

<p>Navy Electronics Laboratory Report 937</p> <p>SLICKS AND TEMPERATURE STRUCTURE IN THE SEA, by E. C. LaFond. 35 p., 2 November 1959. UNCLASSIFIED</p> <p>A study was made at Mission Beach, California, of the relation of sea surface slicks to temperature structure of the sea. It was found that every large internal wave had a slick associated with it, for the thermocline depths observed. Generally, the slick occurred between the crest and the following trough of the wave. The relation was sufficiently reliable to enable the subsurface thermal topography to be predicted approximately from the distribution and movement of the slicks.</p> <p>1. Internal waves 2. Sea water — Temperature 3. Slicks — Temperature factors 1. LaFond, E. C.</p> <p>IO 15401 NE 120221 (NEL L4-1) This card is UNCLASSIFIED</p>	<p>Navy Electronics Laboratory Report 937</p> <p>SLICKS AND TEMPERATURE STRUCTURE IN THE SEA, by E. C. LaFond. 35 p., 2 November 1959. UNCLASSIFIED</p> <p>A study was made at Mission Beach, California, of the relation of sea surface slicks to temperature structure of the sea. It was found that every large internal wave had a slick associated with it, for the thermocline depths observed. Generally, the slick occurred between the crest and the following trough of the wave. The relation was sufficiently reliable to enable the subsurface thermal topography to be predicted approximately from the distribution and movement of the slicks.</p> <p>1. Internal waves 2. Sea water — Temperature 3. Slicks — Temperature factors 1. LaFond, E. C.</p> <p>IO 15401 NE 120221 (NEL L4-1) This card is UNCLASSIFIED</p>
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